

## Recent and Future $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Measurements

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### Overview

Expt      Results or Goal

E787      Completed. 2 candidates.

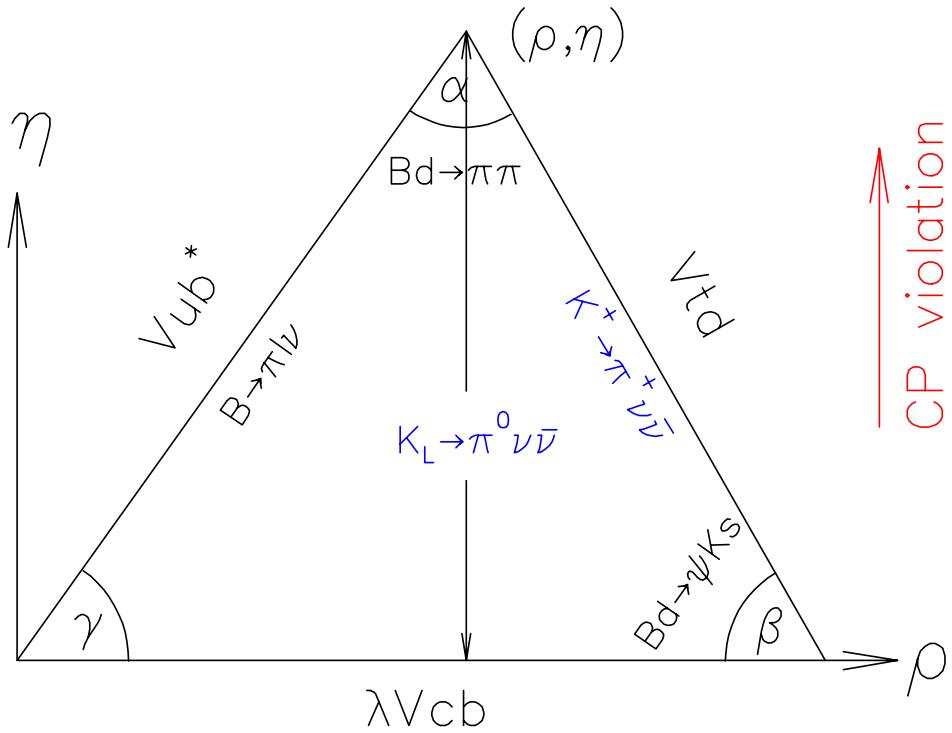
E949      1/5 completed.  $\mathcal{O}(10)$  SM events

CKM      100 SM events,  $S/B \approx 10$

### Outlook

- I'm standing in today for Jingliang Hu from TRIUMPF who, thanks to Homeland Security, couldn't make it here today. Dave Jaffe of BNL and Jingliang kindly provided these slides.
- I am a member of E949 and spokesman of CKM. I can only wish that I were a member of E787.

## “Golden” modes and the CKM unitarity triangle



Process	Expts
$\mathcal{B}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$	KOPIO, E391a
$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$	E787/E949, CKM
$\mathcal{A}(B \rightarrow J/\psi K_S^0; t)$	BaBar, Belle
$\Delta m_s / \Delta m_d$	CDF, D0

Comparison of  $\mathcal{B}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$ ,  $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$  and  $\sin 2\beta$  provides a clean and direct comparison of CP violation between the K and B sectors.

## Measurements and expectations for $K \rightarrow \pi\nu\bar{\nu}$

	$\mathcal{B}(K^+ \rightarrow \pi^+ \nu\bar{\nu})$	$\mathcal{B}(K_L^0 \rightarrow \pi^0 \nu\bar{\nu})$
Measurement	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$ (a)	$< 5.9 \times 10^{-7}$ (b) $< 4.4 \times \mathcal{B}(K^+ \rightarrow \pi^+ \nu\bar{\nu})$ (c)
Expectation	$(0.7 \pm 0.2) \times 10^{-10}$ (d)	$(0.3 \pm 0.1) \times 10^{-10}$ (d)
Limiting Uncert.	5% (f)	1% (f)

Limits are at 90% CL.

### References

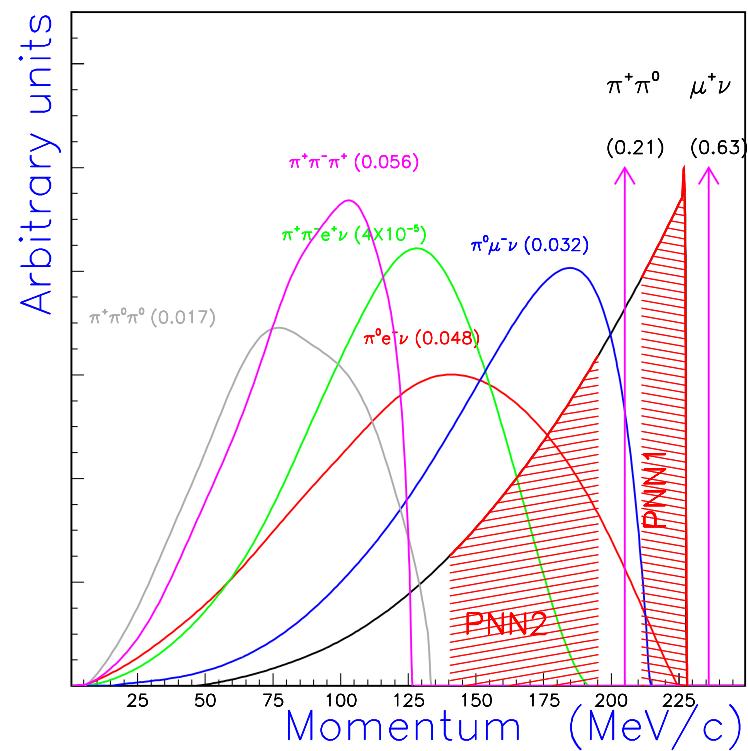
- |                                 |                                 |
|---------------------------------|---------------------------------|
| (a) PRL <b>88</b> (2002) 041803 | (b) PR <b>D61</b> (2000) 072006 |
| (c) PL <b>B398</b> (1997) 163   | (d) hep-ph/0304132              |
| (e) hep-ph/0212321              | (f) hep-ph/0101336              |

Name	“PNN2”	“PNN1”
$P_\pi$ (MeV/c)	[140,195]	[211,229]
Years	1996- <b>97</b>	1995-98
Stopped K <sup>+</sup>	$1.7 \times 10^{12}$	$5.9 \times 10^{12}$
Candidates	1	2
Background	$1.22 \pm 0.24$	$0.15 \pm 0.05$
$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$	$< 22 \times 10^{-10}$	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$

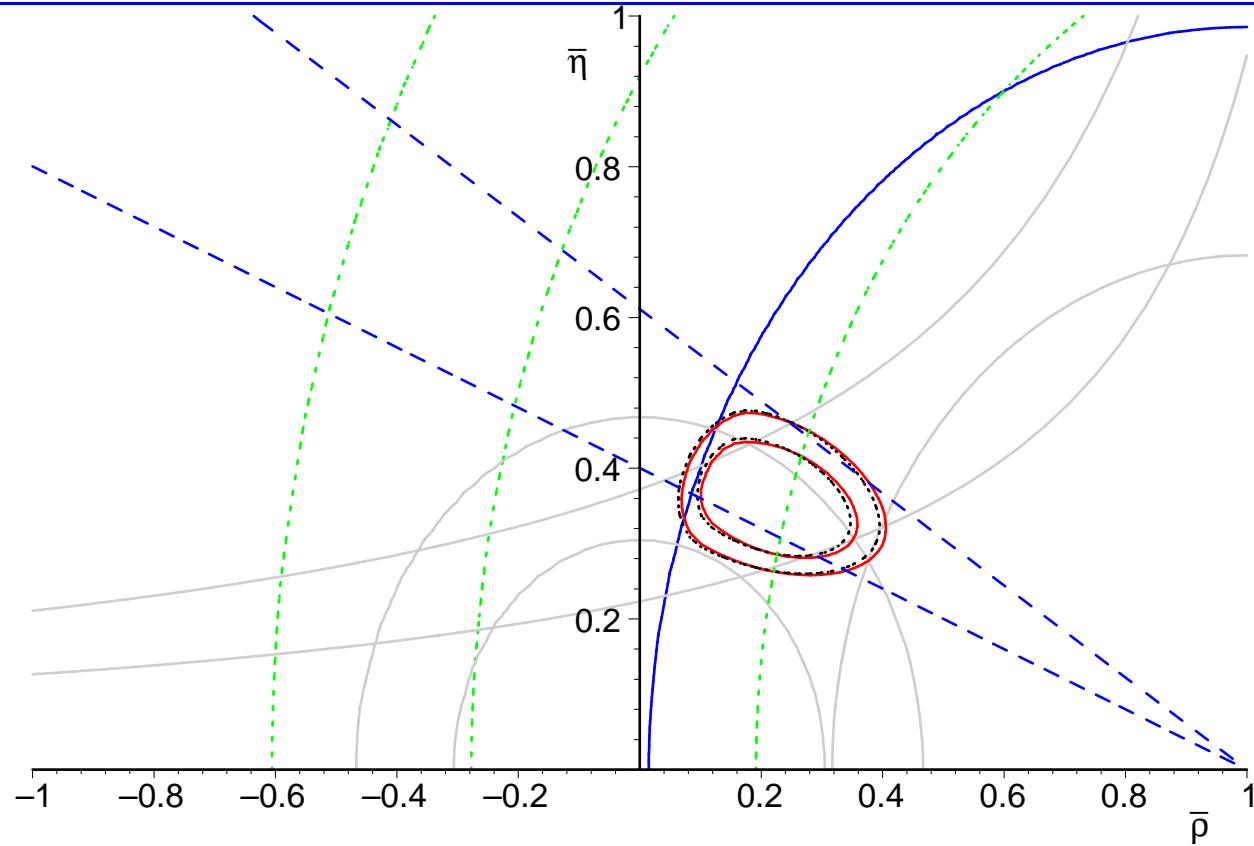
Probability that **PNN1** candidates are entirely due to background is 0.02% (PRL **88**, 041803 (2002)).

Preliminary **PNN2** limit at 90%CL is combined result from 1996 (PL **B537**, 211 (2002)) and **1997** data.

## E787 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ results



## Impact of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ on Unitarity Triangle



68% and 90% CL intervals with (dotted) and without (solid) the  $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$  constraint from **PNN1** region.

G. D'Ambrosio & G. Isidori, PL **B530**, 108 (2002)

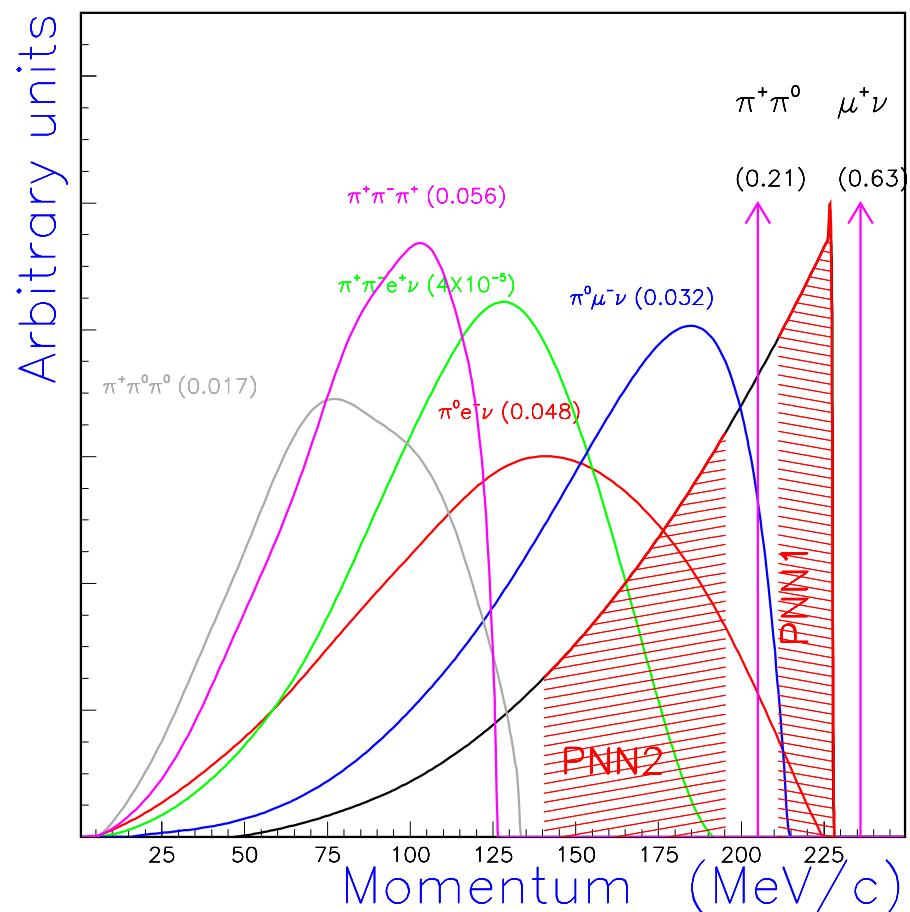
## E787 experimental method

**Measure everything possible.**

- Independent measurements of range(R), energy(E) and momentum(P) of  $\pi^+$
- Positive identification of incoming  $K^+$  and outgoing  $\pi^+$
- Veto extra photons and charged particles

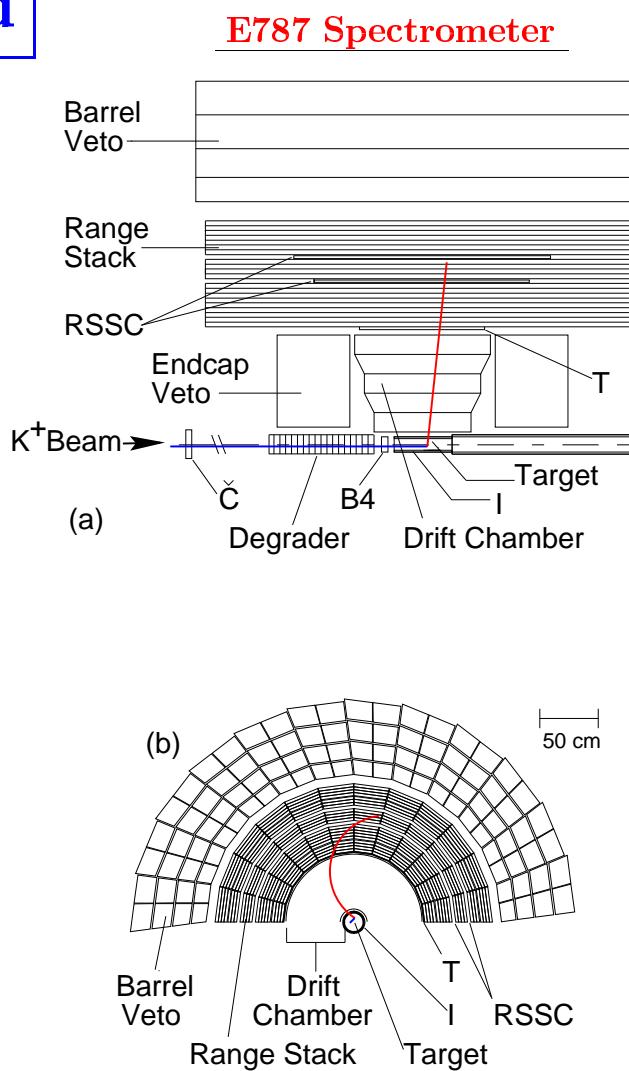
Background must be suppressed by  $10^{11}$ :  $Bkgd/S(SM) < 0.1$

Measure background with data — set cuts based on 1/3 of data and evaluate bkgd with remaining 2/3.



## E787 experimental method

- $\sim 700 \text{ MeV}/c \text{ K}^+$  beam ( $K/\pi \approx 4/1$ )
- Stop  $K^+$  in scint. fiber target
- Wait at least 2 ns for  $K^+$  decay
- Measure  $P$  in drift chamber
- Measure range  $R$  and energy  $E$  in target and range stack (RS)
- Stop  $\pi^+$  in range stack
- Observe  $\pi^+ \rightarrow \mu^+ \rightarrow e^+$  in RS
- Veto photons, charged tracks



## E787 analysis strategy

- A priori identification of background sources.
- Suppress each background source with at least two independent cuts.
- Backgrounds cannot be reliably simulated: measure with data by inverting cuts and measuring rejection taking any (small) correlations into account.
- To avoid bias, set cuts using 1/3 of data, then measure backgrounds with remaining 2/3 sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- Use MC to measure geometrical acceptance for  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ . Verify by measuring  $\mathcal{B}(K^+ \rightarrow \pi^+ \pi^0)$ .
- “Blind” analysis. Don’t examine signal region until all backgrounds verified.

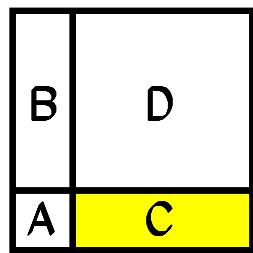
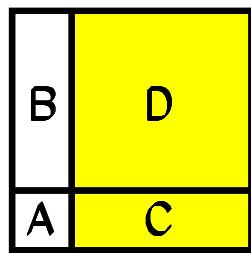
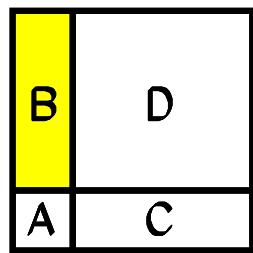
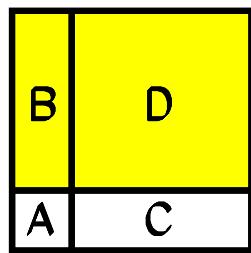
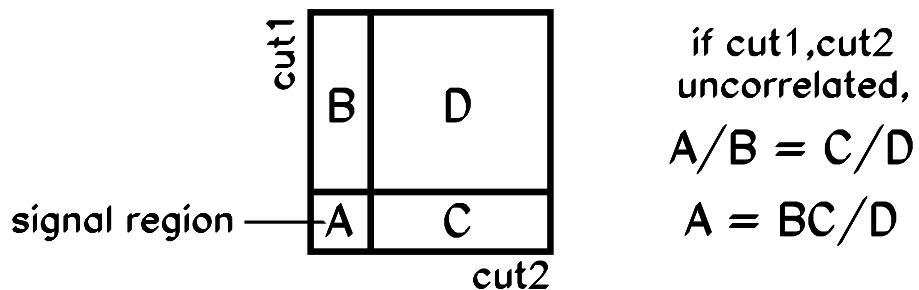
## pnn1 background suppression

Source	Suppression method			
	Kinematics	Particle ID	Veto	Timing
$K^+ \rightarrow \mu^+ \nu(\gamma)$	✓	✓	(✓)	
$K^+ \rightarrow \pi^+ \pi^0$	✓		✓	
Scattered beam		✓		✓
CEX			✓	✓

$$\text{CEX} \equiv K^+ n \rightarrow K^0 p , K_L^0 \rightarrow \pi^+ \ell^- \nu$$

Particle ID includes beam Cherenkov,  $dE/dx$  and  $\pi \rightarrow \mu \rightarrow e$  detection

Veto includes both photon and charged particle vetoing



$$\begin{aligned} bg &= B/(R-1) \\ &= BC/D \end{aligned}$$

## Measuring background with data

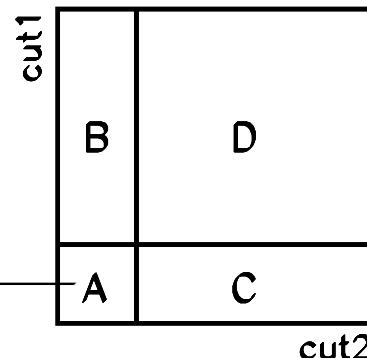
## Measuring background with data

Checking for correlations between cuts.

Compare background predictions with observations near signal region.

$$\text{bg} = BC/D$$

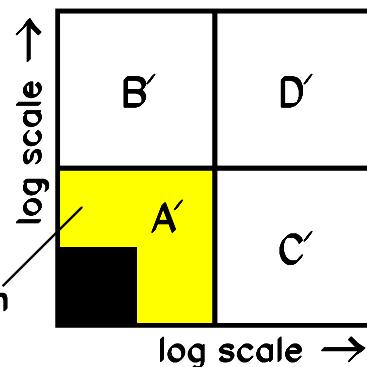
signal region

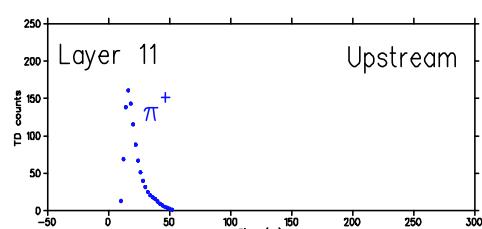
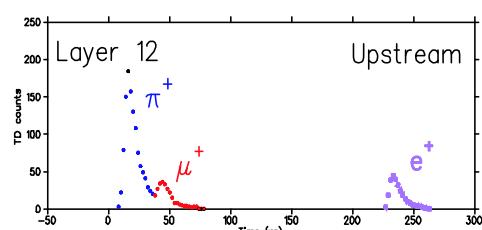
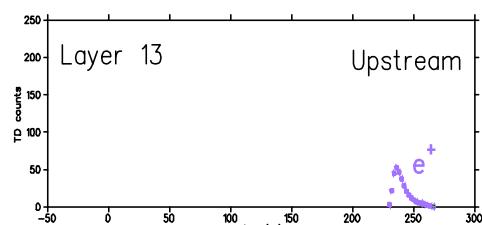
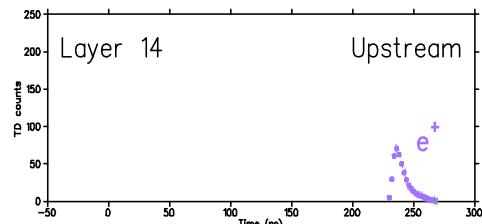


$$\text{bg}' = B'C'/D' - BC/D$$

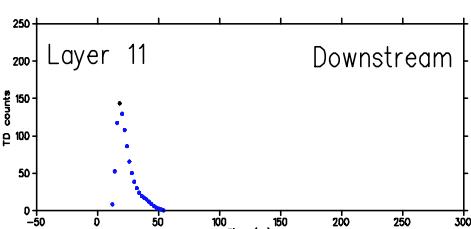
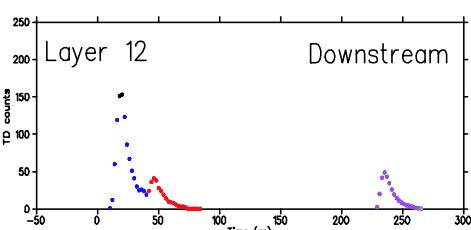
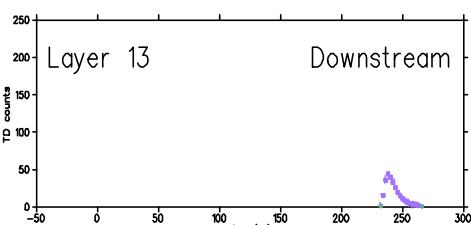
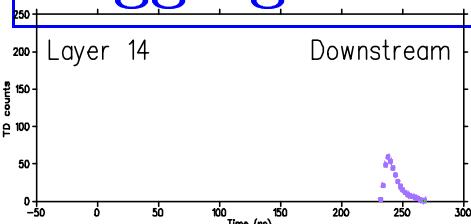
mask out box  
and observe

outside-the-box region





**Tagging  $\pi^+ \rightarrow \mu^+ \rightarrow e^+$**



- Sample pulse height every 2 ns for 6  $\mu$ s

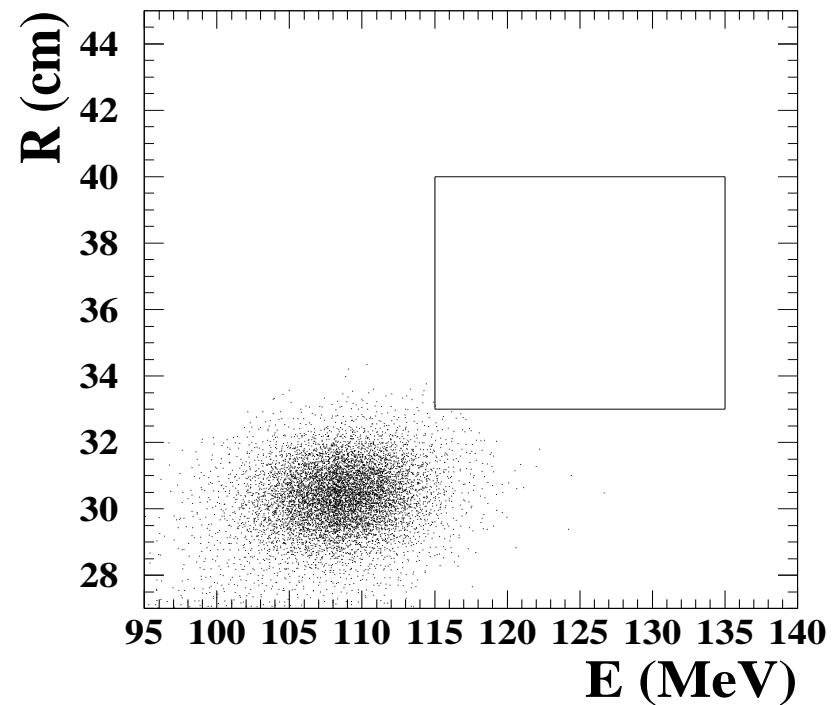
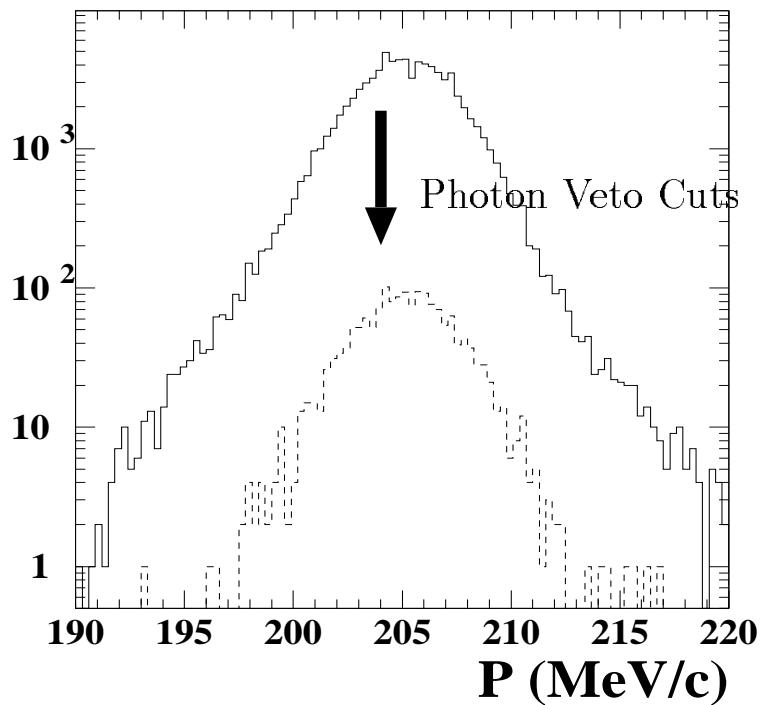
- $\pi^+$  stops in range stack scintillator (2 cm/layer)

- $\pi^+ \rightarrow \mu^+ \nu, E_\mu = 4.1 \text{ MeV}, R_\mu \sim 1 \text{ mm}, \tau_\pi = 26.0 \text{ ns}$

- $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu, E_e \leq 53 \text{ MeV}, \tau_\mu = 2.20 \mu\text{s}$

Plots: Pulse height (0 to 250)  
vs time (-50 to 300 ns)

## $K^+ \rightarrow \pi^+\pi^0$ background rejection

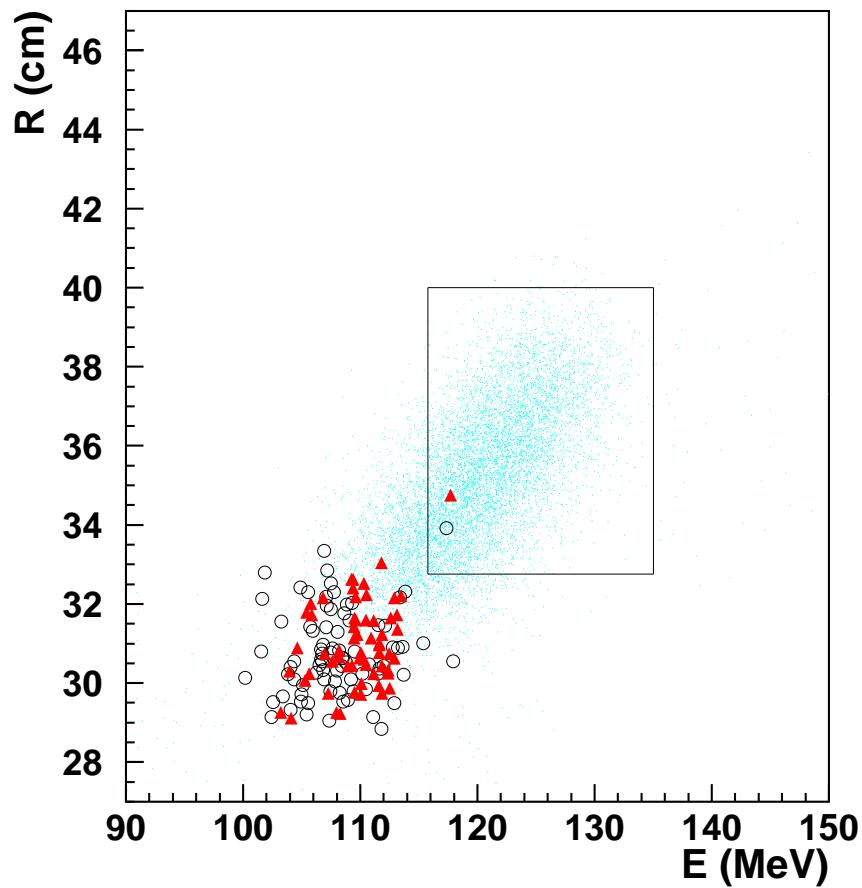


**Left:** Kinematically selected  $K^+ \rightarrow \pi^+\pi^0$  with photon veto applied. Photon veto: Typically 2-5 ns time windows and 0.2 - 3 MeV energy thresholds

**Right:** Photon veto inverted. Phase space cuts in  $P$ ,  $R$ ,  $E$ .

## E787 pnn1 results

Range(cm) vs Energy(MeV) after all other cuts applied.

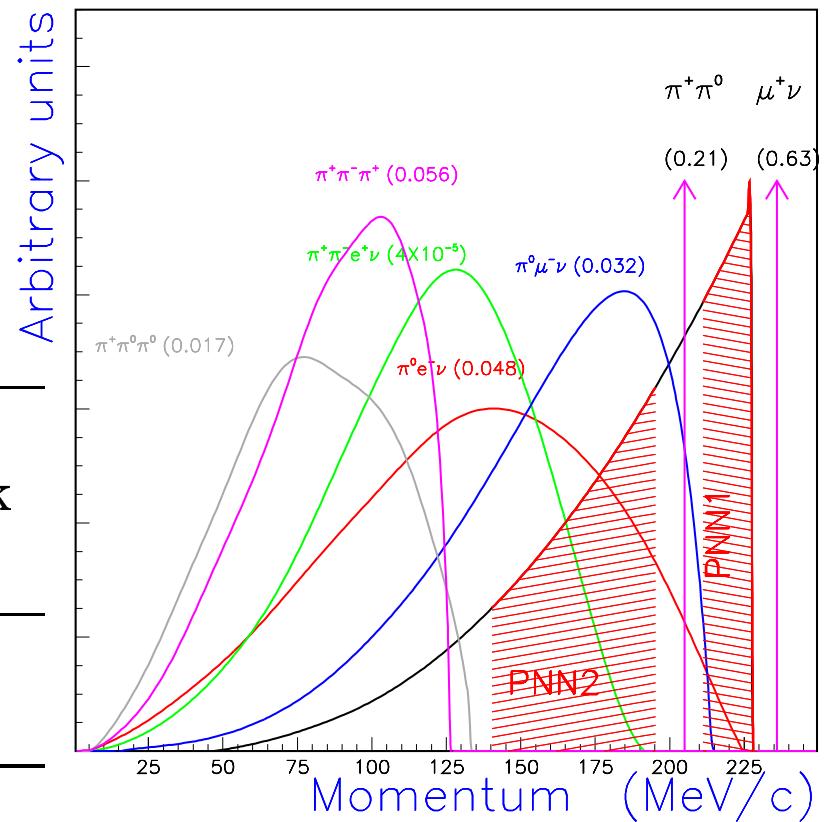


	Bkgd	1995-97	1998
$K_{\pi 2}$	$0.03 \pm 0.01$	$0.012^{+0.003}_{-0.004}$	
$K_{\mu 2}$	$0.02 \pm 0.01$	$0.034^{+0.043}_{-0.024}$	
Beam	$0.02 \pm 0.02$	$0.004 \pm 0.001$	
CEX	$0.01 \pm 0.01$	$0.016^{+0.005}_{-0.004}$	
Total	$0.08 \pm 0.03$	$0.066^{+0.044}_{-0.025}$	
<hr/>			
N(K)	$3.2 \times 10^{12}$	$2.7 \times 10^{12}$	
Acc.	$0.0021(1)(2)$	$0.00196(5)(10)$	
Sens.	$1.5 \times 10^{-10}$	$1.89 \times 10^{-10}$	
Cand.	1	1	
<hr/>			
$\mathcal{B}$	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$		

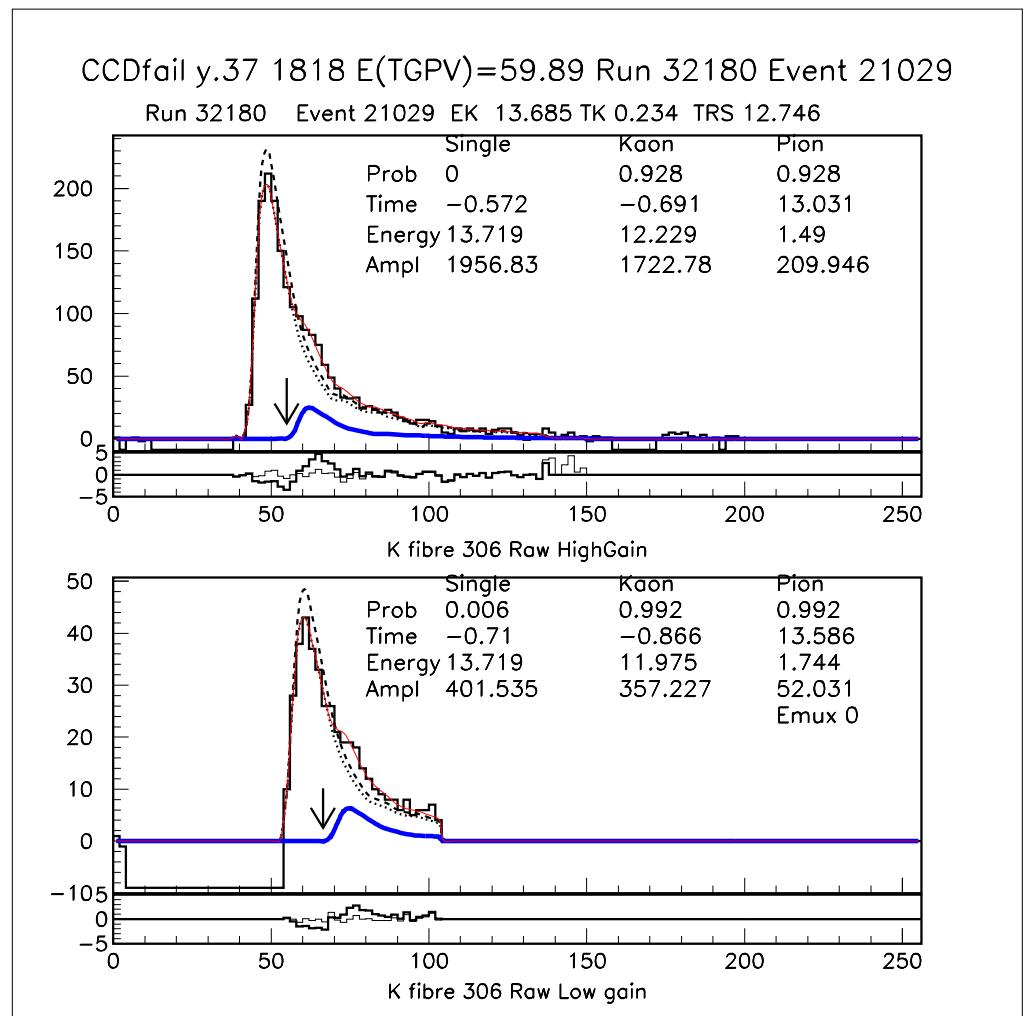
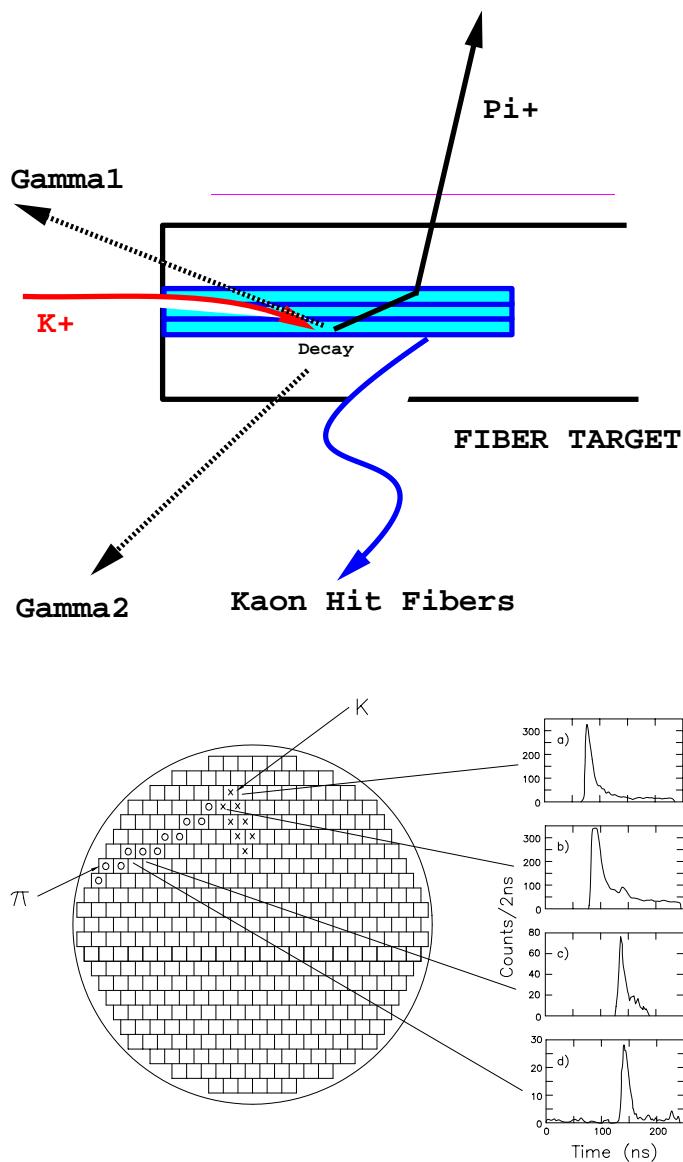
**pnn2:  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  below  $K^+ \rightarrow \pi^+ \pi^0$  peak**

- More phase space than pnn1
- Less loss due to  $\pi^+ N$  interactions
- $P(\pi^+) = (140,195) \text{ MeV/c}$  probes more of  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  spectrum
- **Larger backgrounds:**

Source ( $\mathcal{B}$ )	Bkgd mechanism
$K^+ \rightarrow \pi^+ \pi^0$ (0.21)	$\pi^+$ scatter in target $\pi^+ \pi^0$ not back-to-back both $\gamma$ missed
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$ ( $4 \times 10^{-5}$ )	$\pi^-$ absorbed $e^+$ annihilates
$K^+ \rightarrow \pi^+ \pi^0 \gamma$ ( $2.75 \times 10^{-4}$ )	all $\gamma$ s missed



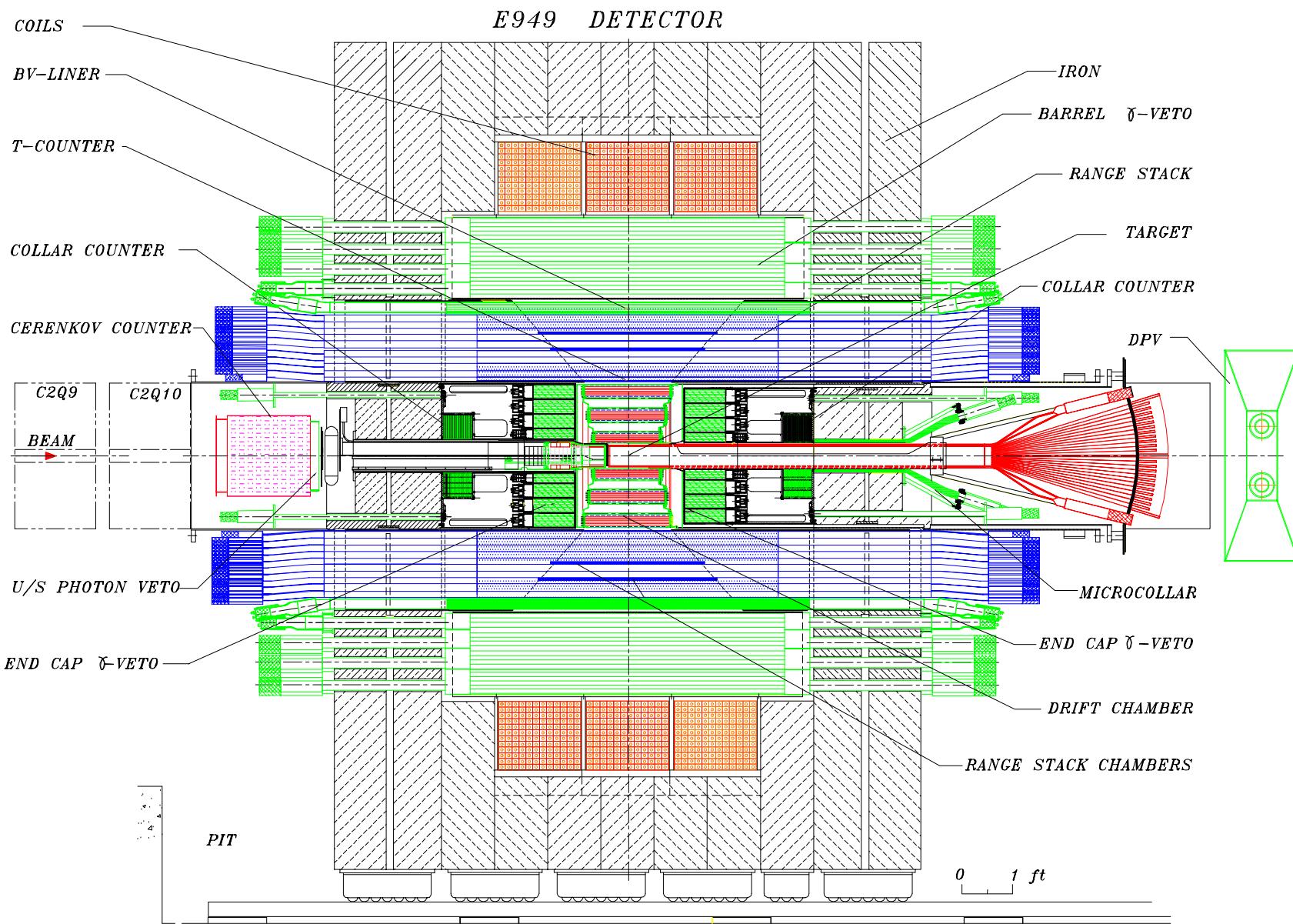
## Suppression of $K^+ \rightarrow \pi^+\pi^0$ scattering background



## pnn2 and pnn1 summary

Backgrounds		
Source	pnn2	pnn1
$K_{\pi 2}$	$1.029 \pm 0.227$	$0.042^{+0.010}_{-0.011}$
Beam	$0.066 \pm 0.047$	$0.024 \pm 0.020$
$K_{e4}$	$0.052 \pm 0.041$	NA
$K_{\pi 2\gamma}$	$0.033 \pm 0.004$	NA
CEX	$0.024 \pm 0.017$	$0.026 \pm 0.011$
$K \rightarrow \mu X$	$0.016 \pm 0.011$	$0.054^{+0.044}_{-0.026}$
Total	$1.22 \pm 0.24$	$0.15 \pm 0.05$
$N(K)$	$1.7 \times 10^{12}$	$5.9 \times 10^{12}$
Cand.	1	2

Factor	Acceptance (Death of $10^3$ cuts)	
	pnn2	pnn1
K stopping eff'y	.683	.703
Delayed $K^+$ decay	.621	.850
Phase space	.345	.146
Solid angle	.315	.408
$\pi$ nucl. int. & d.i.f.	.708	.519
Recon. eff'y	.952	.964
Kinematic cuts	.690	.614
$\pi \rightarrow \mu \rightarrow e$	.526	.345
Beam, target cuts	.199	.702
Accidental loss	.373	.769
Product( $10^{-3}$ )	.835	2.04



## E949 status

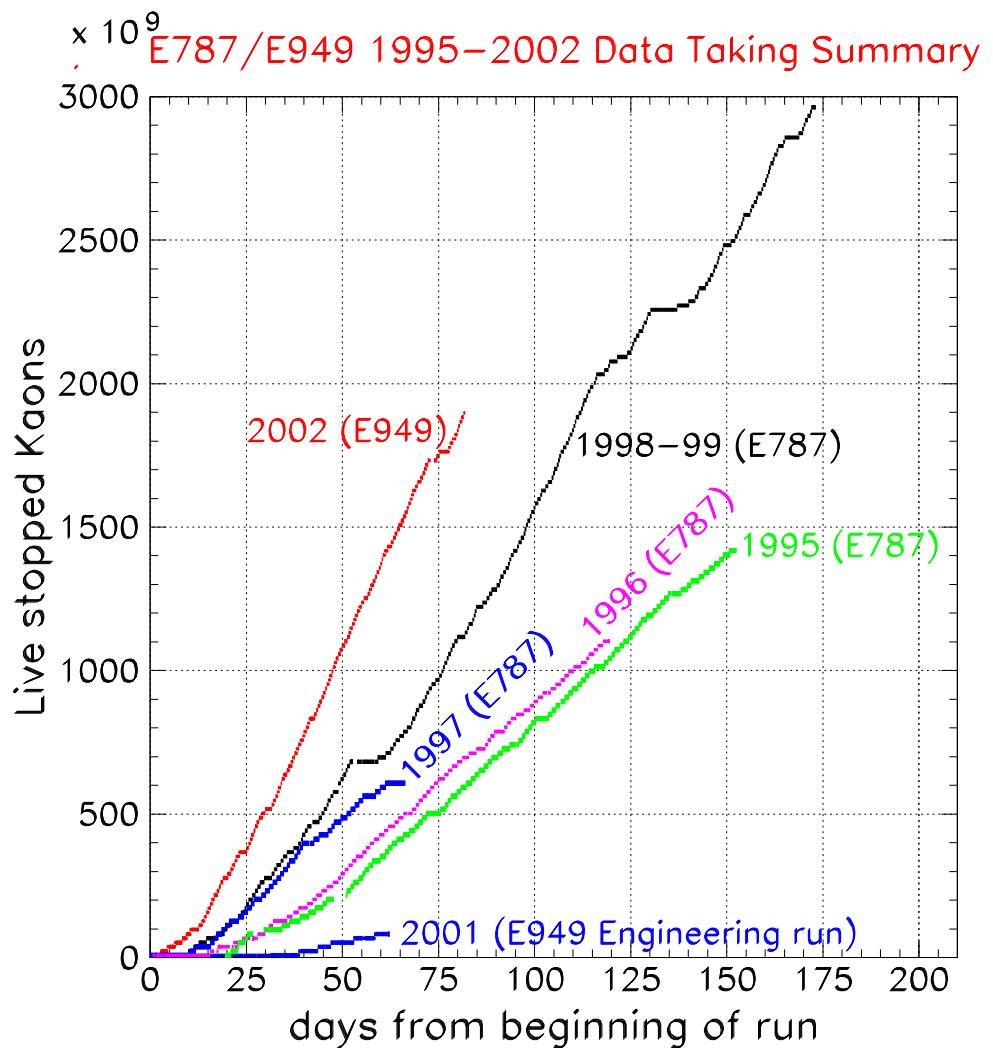
### Upgrades to E787:

Improved photon veto hermeticity  
Improved tracking resolution  
Higher rate and duty factor  
**2002 run**  $\leq$  E787 sensitivity,  
~ 20% of E949 sensitivity goal of  
 $< 10^{-11}$ .

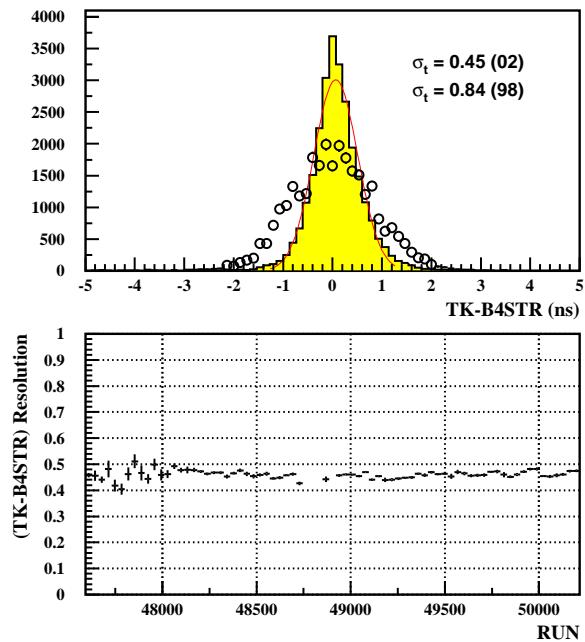
**pnn1 results:** fall 2003.

**Not optimal in 2002:**

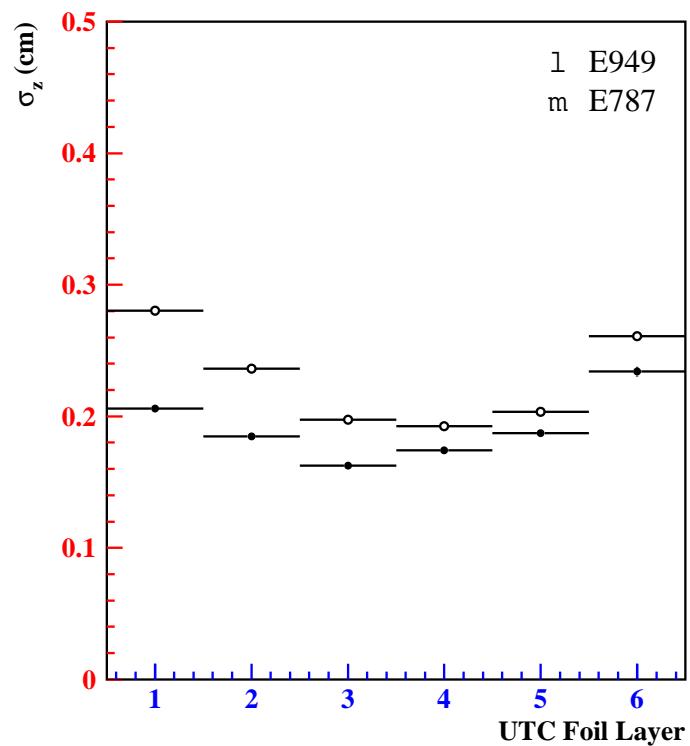
1. Spill duty factor.
2. Proton beam momentum.
3. K/ $\pi$  electrostatic separators.



## E949: Resolution Improvements



Improved target timing resolution for K/ $\pi$  identification.  
 $\sim 2\%$  acceptance gain at high rate



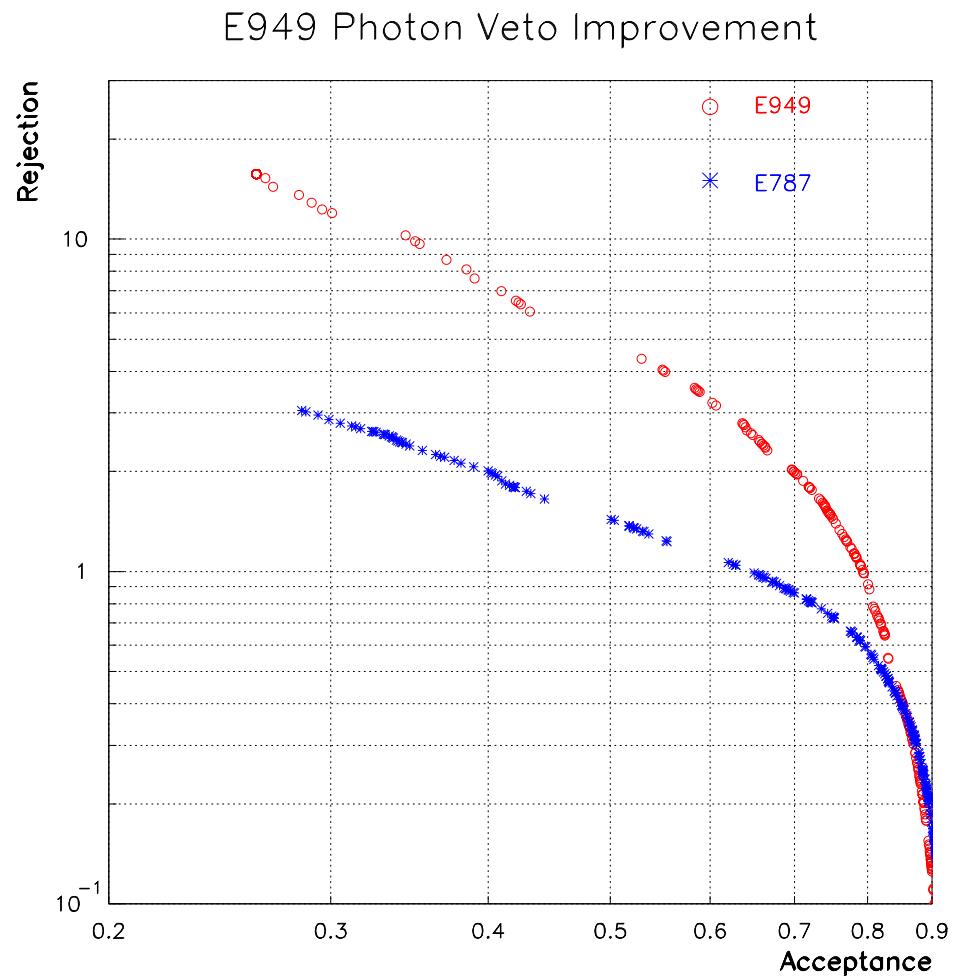
Improved tracking resolution from new UTC electronics

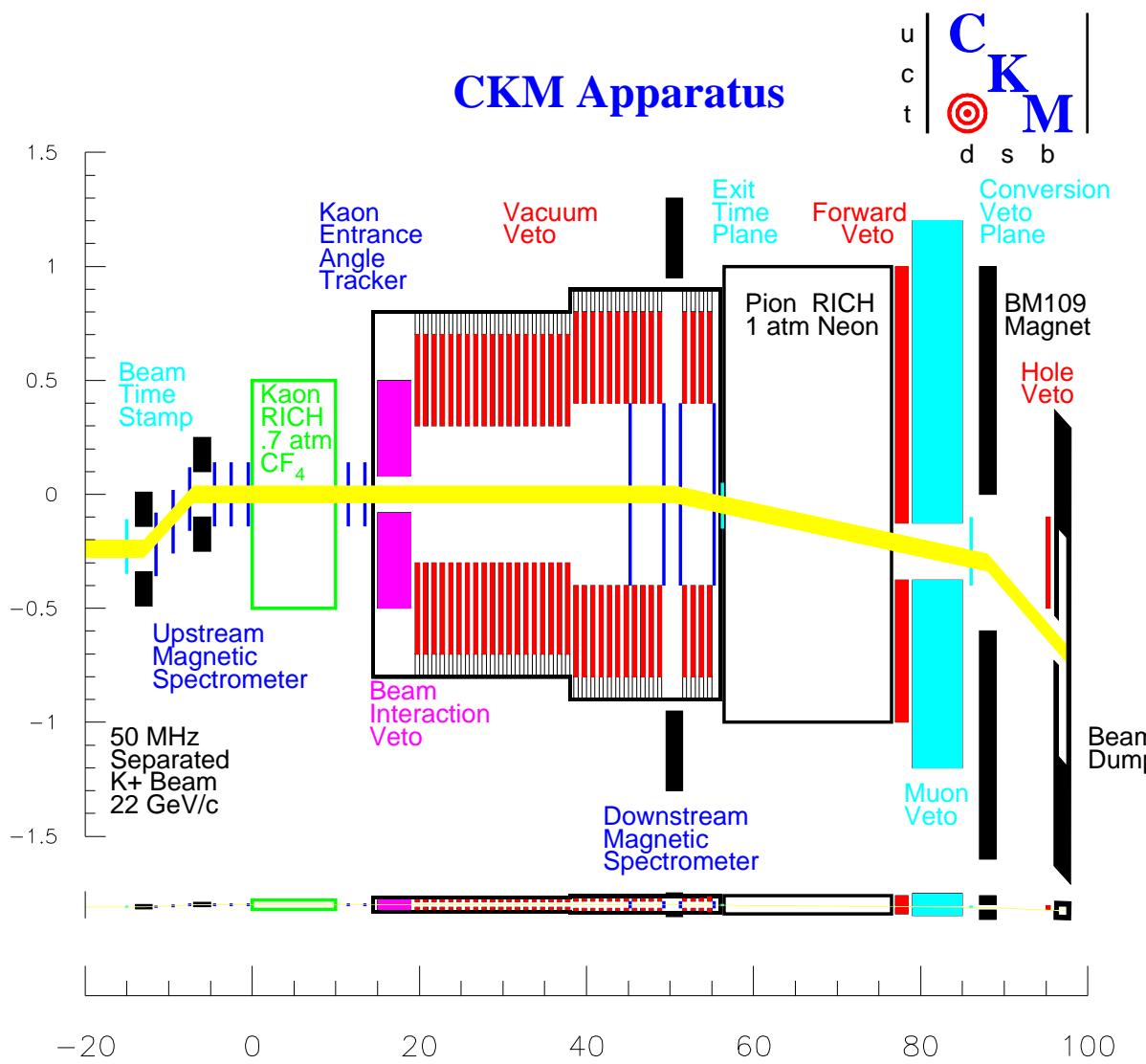
## E949: Upgrade of photon veto

Improved photon veto hermeticity.

Figure: background **Rejection** as a function of  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  signal **Acceptance** for the photon veto cut for E787 and E949.

Preliminary:  $\sim 2\times$  better rejection at nominal **PNN1** acceptance of 80% or  $\sim 5\%$  more acceptance in E949 with same rejection as E787.





## Fermilab CKM Experiment

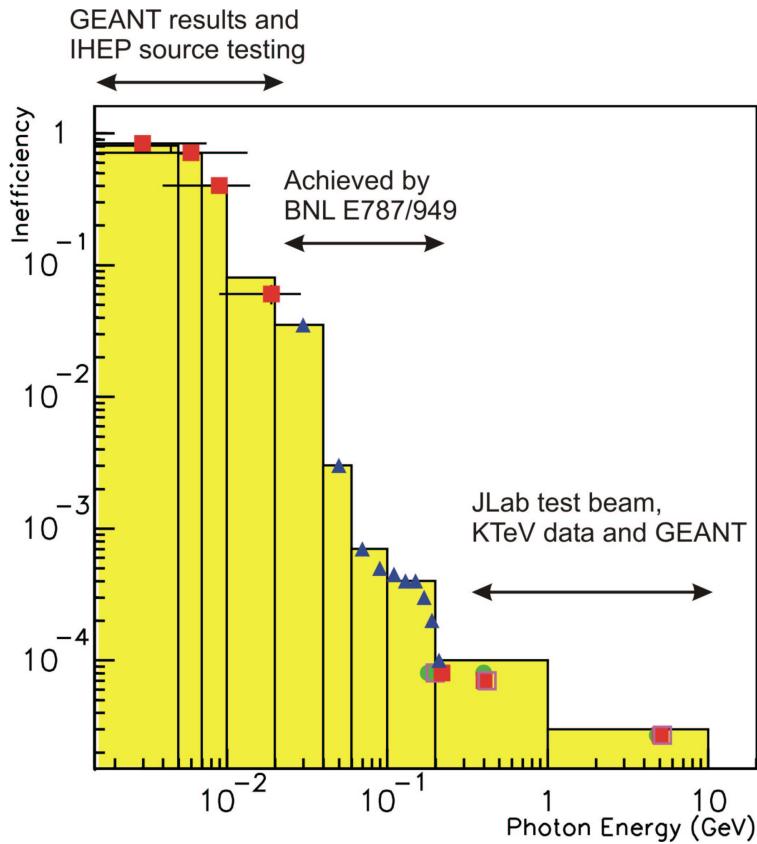
Goal: SES =  $10^{-12}$   
or  $\approx 100$  SM events.

$K^+$  decay-in-flight.

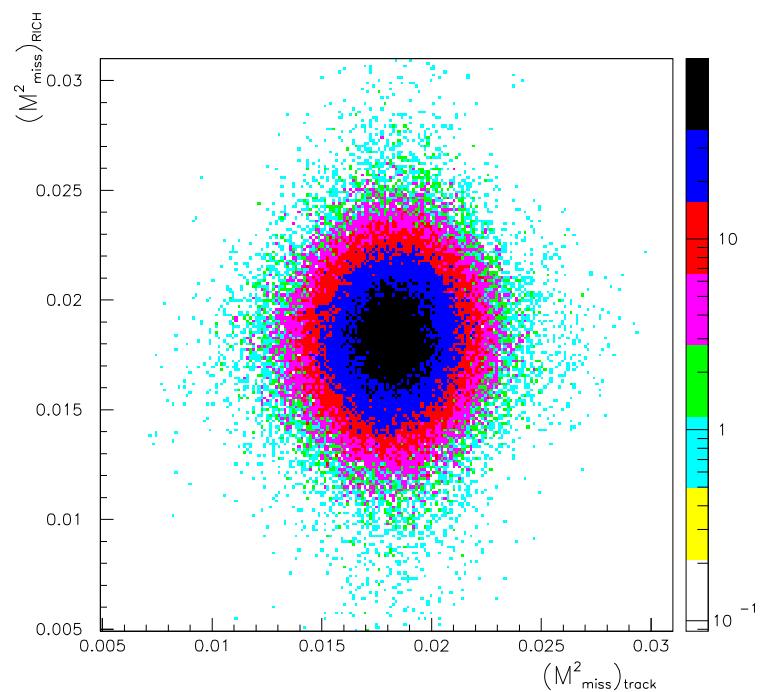
Signal region is above  $K\pi_2$  peak.

Need  $\bar{\epsilon}_{\gamma\gamma} \sim 10^{-7}$   
and  $\bar{\epsilon}_{\text{kine}} \sim 10^{-5}$ .

## CKM: Achieving $\bar{\epsilon}_{\gamma\gamma} \sim 10^{-7}$ and $\bar{\epsilon}_{\text{kine}} \sim 10^{-5}$

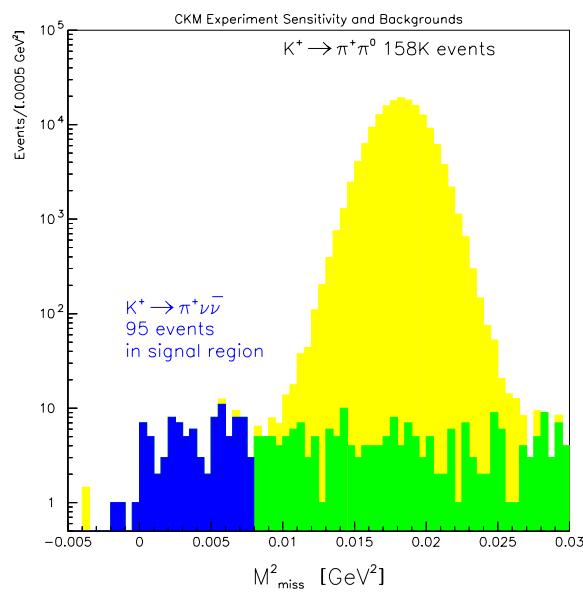


Required(histogram) and achieved(points) photon veto inefficiency.

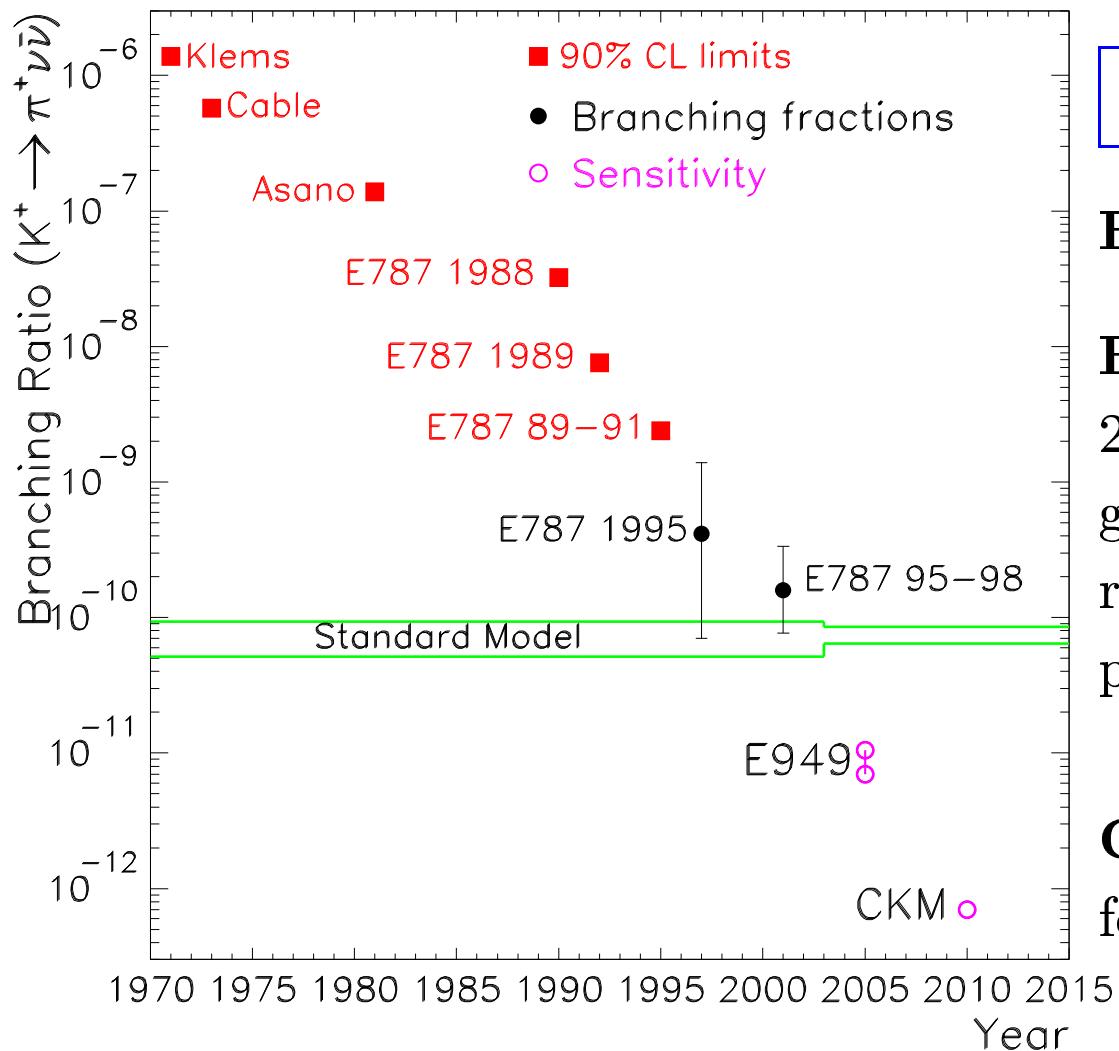


Simulated  $M^2_{\text{miss}}$  for  $K_{\pi 2}$  from tracking (horiz.) and RICH(vert.). Note uncorrelated non-gaussian tails.

## CKM Goal: 100 events with S/N>7



Background source	Effective BR ( $\times 10^{-12}$ )
$K^+ \rightarrow \mu^+ \nu_\mu$	< 0.04
$K^+ \rightarrow \pi^+ \pi^0$	3.7
$K^+ \rightarrow \mu^+ \nu_m u \gamma$	< 0.09
$K^+ A \rightarrow K_L X, K_L \rightarrow \pi^+ e^- \bar{\nu}_e$	< 0.14
$K^+ A \rightarrow \pi^+ X$ in trackers	< 4.0
$K^+ A \rightarrow \pi^+ X$ in residual gas	< 2.1
Accidentals (2 $K^+$ decays)	0.51
<b>Total</b>	< 10.6



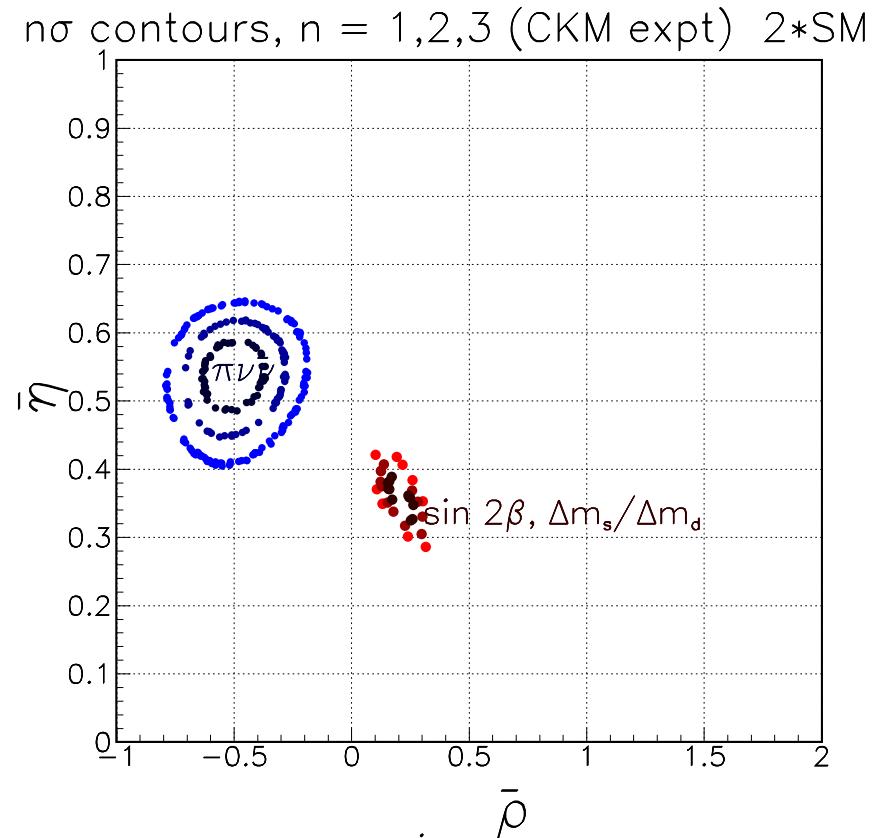
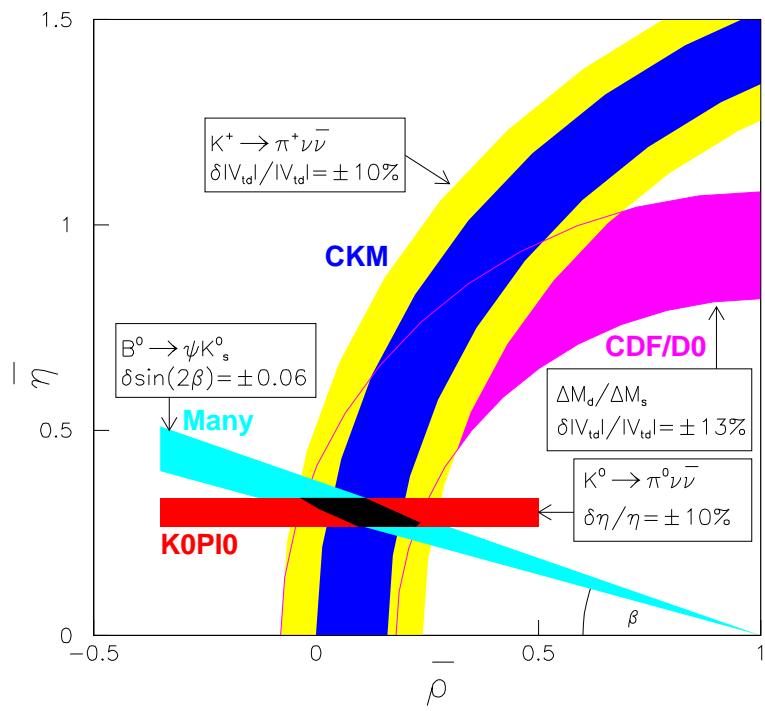
## $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ history

**E787:** completed.

**E949:** 12 week run in 2002, can reach **sensitivity** goal of  $\leq 10^{-11}$  when remaining 48 weeks of approved running is funded.

**CKM:** Start-up scheduled for 2009.

## Possible impact of $K \rightarrow \pi\nu\bar{\nu}$ measurements



All measurements at SM expectation.

$K \rightarrow \pi\nu\bar{\nu}$  rates at twice SM expectation

## Outlook for $K \rightarrow \pi\nu\bar{\nu}$ measurements

E787: completed

**E949:** Approved by DOE(1999), DOE halts HEP at AGS(2002), awaiting funding to continue

**CKM:** Stage I approval(2001), data taking in 2009(?)

**KOPIO:** Approved by NSF(2003), construction start in 2005

**These experiments would be able to test the precise predictions for  $K \rightarrow \pi\nu\bar{\nu}$  branching fractions.**

**Extras**

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = K_+ \left( \left[ \text{Im} \lambda_t \frac{X}{\lambda^5} \right]^2 + \left[ \text{Re} \lambda_c \frac{P_0}{\lambda} + \text{Re} \lambda_t \frac{X}{\lambda^5} \right]^2 \right)$$

$$\mathcal{B}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) = K_0 \left( \left[ \text{Im} \lambda_t \frac{X}{\lambda^5} \right]^2 \right)$$

$$\lambda_i \equiv V_{is}^* V_{id}$$

$$K_+ \equiv r_+ B$$

$$K_0 \equiv r_0 B \tau(K_L^0) / \tau(K^+)$$

$$B \equiv 3\alpha^2 \mathcal{B}(K^+ \rightarrow \pi^0 e^+ \nu) / 2\pi^2 \sin^4 \theta_W$$

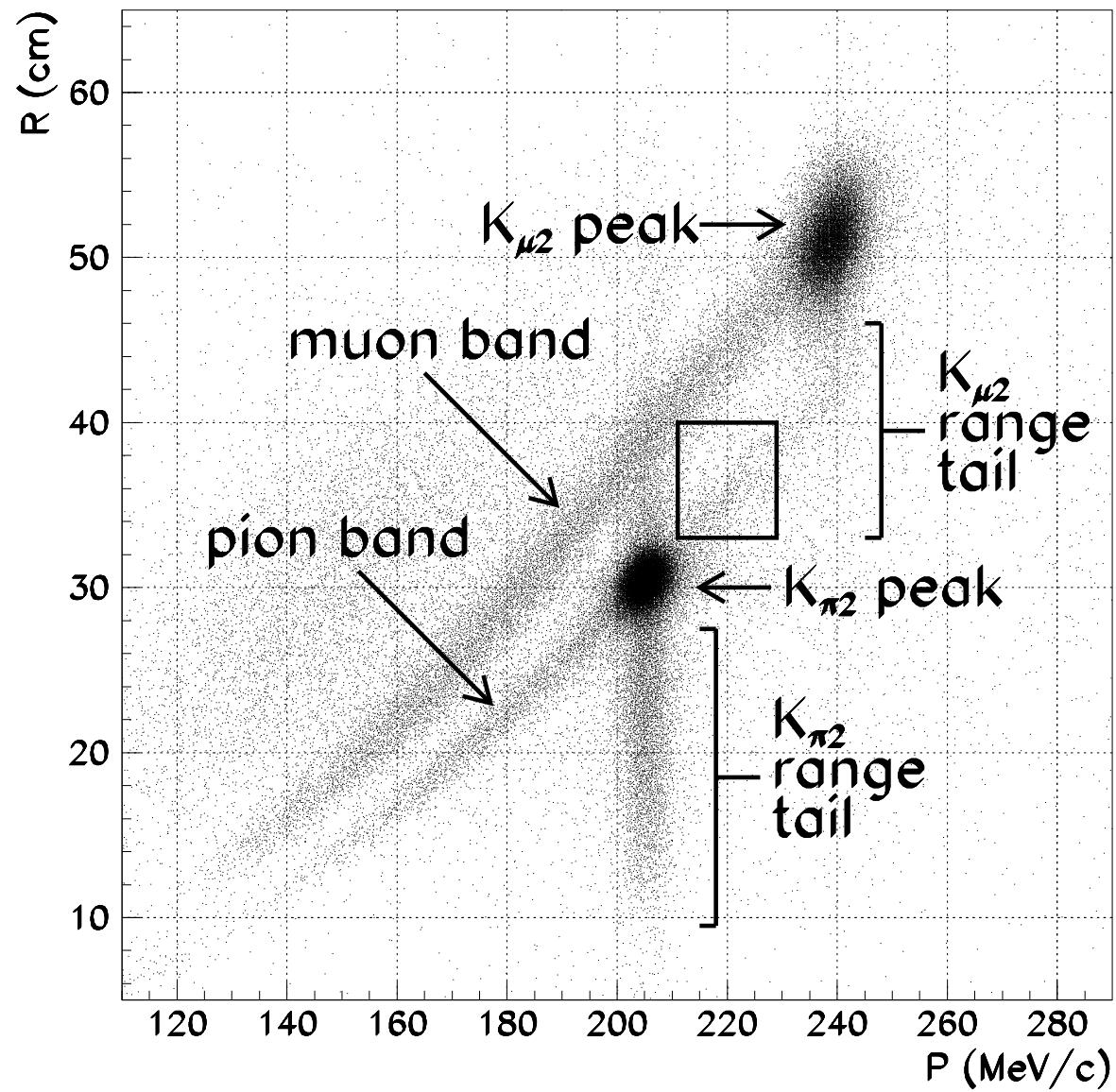
$$X \equiv X(x_t) \equiv \frac{x_t}{8(x_t - 1)} \left( x + 2 + \frac{3x-6}{x-1} \ln x \right)$$

$$x_t \equiv (m_t/m_W)^2$$

$$r_+ = 0.901$$

$$r_0 = 0.944$$

$$P_0 = 0.40 \pm 0.06 \text{ (charm)}$$



Range *vs* Momentum  
accepted by trigger

## Possible impact of $K \rightarrow \pi\nu\bar{\nu}$ measurements

Assume  $K \rightarrow \pi\nu\bar{\nu}$  rates at twice SM expectation and B measurements are consistent with SM.

$$\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (1.57 \pm 0.12) \times 10^{-10}$$

$$\mathcal{B}(K_L^0 \rightarrow \pi^0\nu\bar{\nu}) = (6.0 \pm 0.8) \times 10^{-11}$$

$$\Delta m_s = 17.0 \pm 1.7 \text{ ps}^{-1}$$

$$\sin 2\beta = 0.70 \pm 0.02$$

